N-63-4-4

RESEARCH ON MILLIMETER FERROMAGNETIC TYPE PARAMETRIC AMPLIFIER
(Unclassified)

Contract No. DA-36-039 SC 89071

Subtask No. 1G6-22001-A-055-05-02

Report No. 9

(Continuation of Contract No. DA-36-039 SC 87401)

Fifth Quarterly Progress Report

1 February 1963 to 30 April 1963

July 1963

Prepared for

U.S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
Fort Monmouth, New Jersey

By

WESTINGHOUSE ELECTRIC CORPORATION
Air Arm Division
Baltimore, Maryland

A-51019AY-5A
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In Accordance With Technical Requirements No. SCL-5795,
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The objective of this research program is to investigate the feasibility of achieving parametric amplification in the millimeter frequency region using a ferromagnetic material as the coupling element.

Prepared by:

Robert A. Moore
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1. PURPOSE

This study is investigating techniques for ferromagnetic parametric amplification in the millimeter-wave frequency region. Attention is being given to the improvement of the performance of discrete amplifiers. New ferromagnetic materials and new configurations particularly suited to millimeter-wave application are being investigated. Emphasis is being given to traveling-wave parametric amplification utilizing ferromagnetic propagation structures.

2. ABSTRACT

Work has continued on the parallel-pumped magnetodynamic amplifier utilizing the dielectric rod uniform precessional mode resonance. In an initial analysis, the pump power has been computed and is presented in curve form in terms of the dielectric resonator Q and ferrimagnetic line width.

The computer solution is given for the propagation characteristics of a dielectric rod. The curves for the dielectric constant of most immediate interest (ϵ_r = 13.5) are corroborated by experimental spectroscopy of Stycast. Dielectric continuity with YIG makes this material appealing for the design of resonant structures capable of supporting simultaneous electromagnetic and magnetostatic resonances. Results of loss tangent measurements of Stycast and other materials are given for 70 kmc and scale frequencies. Ways of coupling energy into the dielectric and magnetostatic modes were studied; experiments are discussed which resulted in the decision to couple to the pump mode from an iris in the side of the waveguide into the end of the rod and to couple to the YIG sphere directly from the side. A 10-kw, 70-kmc magnetron is being used to provide pumping power and has been tested at the 3.2-kw level in pressurized waveguide. The signal circuit, in addition to isolation through amplifier configuration, contains cascaded E-H tuners which provide a dynamic range of more than 15 db. Two mechanisms for tuning the resonance of the rod are available.

3. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

On 15 February 1963 a conference was held in Baltimore between Dr. Martin Auer of USAELRDL and Dr. R. A. Moore of Westinghouse to discuss progress on the magnetodynamic mode amplifier under construction.

On 16 April 1963 Mr. John Carter of USAELRDL visited Westinghouse to discuss with Dr. R. A. Moore progress of the experimental work and possible analytical extension of the effort.

4. FACTUAL DATA

4.1 INTRODUCTION

Since the beginning of this program it has appeared that an important factor for reduction of pump power in ferrimagnetic amplifiers would be through maximizing the filling factor. In line with this approach work for the present period has concentrated on developing and putting into operation a parallel-pumped amplifier which utilizes a dielectric rod resonant structure with a sphere of single-crystal YIG embedded.

The concept for this structure arose from the original suggestion that the total resonant structure for concentrating the fields be a ferrite rod of suitable dimensions to provide appropriately related simultaneous resonances. A dispersion analysis of some lower order modes of this structure has been conducted by a digital computer program with some reasonably good experimental correlation. An approach was described in Report No. 7 for obtaining suitable simultaneous resonances, and an example was carried through.

While work is in progress for developing suitable operating conditions for the ferrite rod structure, work on the dielectric rod structure has been directed toward establishing appropriate operating conditions, developing dielectric and metallic parts, and preparing associated pump and signal circuitry for testing the amplifier. The initial mode of operation chosen for study is a parallel pump mode in which a dielectric resonance of the structure and the uniform precessional mode of the ferromagnetic resonator are used to support the signal and idler fields. The pump will be supported on the H_{01} mode of the dielectric structure. This mode of operation might be considered a semistatic parallel pump mode. The following is an analysis of the operation of this mode.

4.2 ANALYSIS

Electromagnetic resonators can be constructed from sections of infinite structures. These structures must be satisfied by Maxwell's equations. The result is an infinite set of orthogonal modes which satisfy the geometry. We shall assume that these modes satisfy the condition

$$\int \bar{E}_{o\alpha} \cdot \bar{E}_{o\beta}^{*} \, dv = \delta_{\alpha\beta} \tag{1}$$

$$\frac{1}{I_\alpha} \int \bar{H}_{o\alpha} \cdot \bar{H}_{o\beta}^{*} \, dv = \delta_{\alpha\beta}$$

where $\delta_{\alpha\beta}$ is equal to unity if $\alpha = \beta$ and is equal to zero, otherwise; I_α is a normalizing function for $\int \left|\bar{H}_{o\alpha}\right|^2 dv$, and $\bar{H}_{o\beta}^{*}$ represents the complex conjugate. The $\bar{H}_{o\alpha}$ will be purely geometric variables. The field representation of the normal modes can then be given as

$$h_\alpha = \left[\bar{H}_{o\alpha} e^{i \omega_\alpha t} - \bar{H}_{o\alpha}^{*} e^{-i \omega_\alpha t}\right] e^{-\frac{t}{T_\alpha}}$$

where T_α is the relaxation time.

For this structure, Maxwell's equations can be written

$$\nabla \times \bar{e} = -\mu_o \frac{\partial}{\partial t} (\bar{h} + \bar{m}) \qquad \nabla \times \bar{h} = \epsilon \frac{\partial \bar{e}}{\partial t} \tag{2}$$

$$\nabla \cdot \bar{b} = 0 \qquad \nabla \cdot \bar{e} = 0$$

where it is assumed that the charge density ρ is zero in the medium. The magnetic moment represents the interaction of the ferrimagnetic resonator on the dielectric resonance. In the unperturbed resonator, this interaction is zero. If we assume $\bar{m}$ is zero, by solving simultaneously, the response in normal mode representation of the dielectric resonant structure can be expressed as

$$\nabla^2 \bar{F}_{o\alpha} = +\left(\frac{-1}{T_\alpha} + i\,\omega_\alpha\right)^2 \bar{F}_{o\alpha} \tag{3}$$

and the complex conjugate where $\bar{F}_{o\alpha}$ can be the geometric representation of either the electric or magnetic field distribution. The exact representation will depend upon the geometry. In principle, an infinite set of modes is possible. In any practical situation, only a finite number of modes can exist for the operating frequency selected.

Let us represent by the summation

$$\bar{f} = \sum_{\alpha=0}^{n} \left[A_\alpha \bar{F}_{o\alpha} e^{i\,\omega_\alpha t} + A_\alpha^* \bar{F}_{o\alpha}^* e^{-i\,\omega_\alpha t} \right] \tag{4}$$

the form of the electric and magnetic field distributions of modes which can exist on the structure. The coefficient A represents slowly varying functions of time. If this representation of the field structure and equation 3 are substituted into equation 2, for the response in the presence of magnetostatic resonance, the following result is obtained

$$\mu_o\,\epsilon \sum_{\alpha=0}^{n} \left[A_\alpha \left(\frac{-1}{T_\alpha} + i\,\omega_\alpha\right)^2 \bar{H}_{o\alpha}\, e^{i\,\omega_\alpha t} + A_\alpha^* \left(\frac{-1}{T_\alpha} - i\,\omega_\alpha\right)^2 \bar{H}_{o\alpha}^*\, e^{-i\,\omega_\alpha t} \right] \tag{5}$$

$$= \mu_o\,\epsilon \sum_{\alpha=0}^{n} \left[\bar{H}_{o\alpha}\, e^{i\omega t} \left(\frac{\partial^2}{\partial t^2} + i\,2\omega \frac{\partial}{\partial t} - \omega^2 \right) A_\alpha \right.$$

$$\left. + \bar{H}_{o\alpha}^*\, e^{-i\,\omega t} \left(\frac{\partial^2}{\partial t^2} - i\,2\,\omega \frac{\partial}{\partial t} - \omega^2 \right) A_\alpha^* \right] + \mu_o\,\epsilon \frac{\partial^2}{\partial t^2} \bar{m}$$

Equation 5 represents the dynamic response of the dielectric resonant structure in terms of its normal mode response $\bar{H}_{o\alpha}$ and slowly varying functions of time A(t) in the presence of a ferrimagnetic interaction $\bar{m}$.

We can simplify this equation substantially by neglecting the second order derivatives of A(t) and assuming operation at the resonant frequency $\omega = \omega_a$. When these substitutions are made

$$- \sum_{a=0}^{n} 2 i \omega_a \bar{H}_{oa} e^{i \omega_a t} \left(\frac{\partial}{\partial t} + \frac{1}{T_a} \right) A_a + \sum_{a=0}^{n} 2 i \omega_a \bar{H}_{oa}^{*} e^{-i \omega_a t} \left(\frac{\partial}{\partial t} + \frac{1}{T_a} \right) A_a^{*}$$

$$= \frac{\partial^2}{\partial t^2} \bar{m} \tag{6}$$

The response of the ferrimagnetic material will be expressed in terms of the equation of motion

$$\frac{d\bar{m}}{dt} = \gamma \, \bar{m} \times \bar{h} \tag{7}$$

The fields in each of the coordinate directions can be represented as

$$H_z = H_o + h_p \tag{8}$$

$$h_x = h_{x1} + h_{x2}$$

$$h_y = h_{y1} + h_{y2}$$

$$m_x = m_{x1} + m_{x2}$$

$$m_y = m_{y1} + m_{y2}$$

$$M_z = M_o$$

where the dc magnetizing field and the pump field, h_p, are oriented in the z direction. The numerical subscripts designate component fields, respectively, the signal and idler modes. The quantities represented in equation 8 are real time variables and individually can be written as

$$h_k = A_\alpha H_{k\alpha} e^{i \omega_\alpha t} + A_\alpha^* H_{k\alpha}^* e^{-i \omega_\alpha t} \tag{9}$$

$$m_k = B_\beta M_{k\beta} e^{i \omega_\beta t} + B_\beta^* M_{k\beta} e^{-i \omega_\beta t}$$

If equations 8 and 9 for the field representation are substituted into equation 7

$$\frac{d M_{xi}}{dt} = \gamma \left[\left(M_{yi} + M_{yj}^*\right)\left(H_o + H_p\right) - M_o H_{yi}\right] \tag{10}$$

$$\frac{d M_{yi}}{dt} = \gamma \left[M_o H_{yi} - \left(M_{xi} + M_{xj}^*\right)\left(H_o + H_p\right)\right]$$

and the complex conjugate, where the subscripts i, j refer to 1, 2, respectively, or vice versa. Only those components for which the frequency response can be ω_i have been retained. Further simplification is possible by recognizing that, in the absence of the pump field intensity, $d M_{xi}/dt = i \omega M_{xi}$ and $d M_{yi}/dt = i \omega M_{yi}$ are, respectively, equal to the right hand sides of equation 10 with H_p set equal to zero. If this substitution is made and again only terms retained for which the contribution is for the frequency ω_i, the following simplified form can be obtained

$$\frac{d M_{xi}}{dt} = i \omega_i M_{xi} + \gamma M_{yj}^* H_p \tag{11}$$

$$\frac{d M_{yi}}{dt} = i \omega_i M_{yi} - \gamma M_{xj}^* H_p$$

For the uniform precessional mode, the normal response is circularly polarized. At this point, we can conveniently use the complex notation

$$\psi^{\pm} = \psi_x \pm i \psi_y \tag{12}$$

In terms of the complex notation of (12), equation 11 can be rewritten

$$\frac{d M_i^{\pm}}{dt} = i\,\omega_i\, M_i^{\pm} \mp i\,\gamma\, H_p\, M_j^{\mp *} \tag{13}$$

and the complex conjugates. It is evident that if the normal resonant response of M_i is the positive direction of rotation, the parametric interaction will be in the negative direction of rotation. If we assume that this component arises from presence of fields of an electromagnetic mode, M_j^{-*} can be written as $X^{-*} A_j^{*} H_{oj}^{-*}$. Also since $H_j^{-*} = A_j^{*} H_{oj}^{-*} e^{-i\,\omega_j\, t}$ and $M_i^{+} = B_i\, M_{oi}^{+} e^{i\,\omega_i\, t}$ where A_j, B_i are slowly varying in time, equation 13 can be written

$$M_{oi}^{+}\left(\frac{\partial}{\partial t} + \frac{1}{T_i}\right) B_i = \mp i\,\gamma\, H_p\, A_j^{*}\, X^{-*}\, H_{oj}^{-*} \tag{14}$$

and the complex conjugate, where T_i is the relaxation for the unperturbed resonance response of M_i.

The response of the electromagnetic mode in equation 6 can now be expanded in terms of the magnetic moment. Substituting in equation 13

$$H_{oy}^{-}\left(\frac{\partial}{\partial t} + \frac{1}{T_a}\right) A_j = \frac{-i\,\gamma\, H_p\, M_{oi}^{+*}\, B_i^{*}}{2} \tag{15}$$

and the complex conjugate. The direction of rotation has been chosen to appropriately interact with equation 14. The terms arising from the direct response in the negative direction of rotation, $i\,\omega_i\, M^{-*}$, have been neglected from equation 13 as they would only add a small perturbation to the resonant frequency.

If we now multiply equations 14 and 15 by appropriate complex conjugate quantities and integrate over the respective volumes, after simultaneous solution we obtain the result

$$\left(\frac{\partial}{\partial t} + \frac{1}{T_i}\right)\left(\frac{\partial}{\partial t} + \frac{1}{T_j}\right) F_a = \frac{\gamma^2 H_p^2 X^{-*}}{2}\, \frac{\left|\int M_{oi}^{+} H_{oj}^{-}\, dv\right|^2 F_a}{\int \left|M_{oi}^{+}\right|^2 dv \int \left|H_{oj}^{-}\right|^2 dv} \tag{16}$$

The integrand for each integral involving magnetic moments is zero except over the volume of the ferrimagnetic resonator. The integral of $|H_o^-|^2$ is taken over the total volume of the field distribution of the electromagnetic resonator.

If it is assumed that over the volume of the ferrimagnetic resonator, the field distribution is essentially uniform, the integrals involving the magnetic moments can be replaced by the product of the volume and the respective integrands. In the remaining integral H_{oj}^- can be replaced by $H_o^- G_j (r, \theta, z)$ where H_o^- is the peak value and G_j is a distribution function. The integrals thus become an equivalent filling factor which we shall represent by K_{ij}.

The threshold of amplification occurs when the rate of parametric energy conversion is just great enough to overcome the losses in the coupled resonant structure. If the relaxation times, T_i, are for the unloaded resonances, the threshold of amplification occurs when the derivatives with respect to time are zero. After rearranging and making these substitutions, the threshold RF magnetic field can be expressed as

$$h_p^2 = \frac{\omega_\alpha \omega_p \Delta H}{4 \gamma \omega_m Q_\alpha K_{ij}} \tag{17}$$

It is now possible to determine, approximately, the pump power required for the threshold of amplification. If the expression for Q is rearranged the power absorbed by the pump cavity can be written

$$P_p = \frac{\omega_p W_p}{Q_p} \tag{18}$$

where W_p is the peak energy stored in the pump cavity or

$$(\mu_o/2)\int |H_p|^2 dv \approx (\mu_o/2) |H_p|^2 V_p/2 \tag{19}$$

where the rms magnetic field is assumed to be $1/\sqrt{2}$ the peak field intensity. The power absorbed by the pump cavity can then be written

$$P_p = \frac{\omega_p \mu_o V_p |h_p|^2}{4 Q_p} \tag{20}$$

$$= \frac{\omega_p^2 \mu_o \omega_i \Delta H V_p}{\gamma \omega_m H_o Q_p Q_i K_{ij}}$$

In order to evaluate equation 20 it has been assumed that the field distribution is almost totally coupled to the dielectric structure so that V_p is essentially the dielectric structure. Further, the field distribution has been assumed uniform over the volume of the ferrite resonator so that K_{ij} is just the ratio of the ferrite to dielectric volume. The computation has been carried out for YIG and the results plotted in figure 1 as a function of $Q = Q_p = Q_i \approx 1/\tan \delta$ of the dielectric cavity with the line width of the YIG as a parameter. The line width is designated according to the 3 kmc line width and assumed to be proportional to frequency.

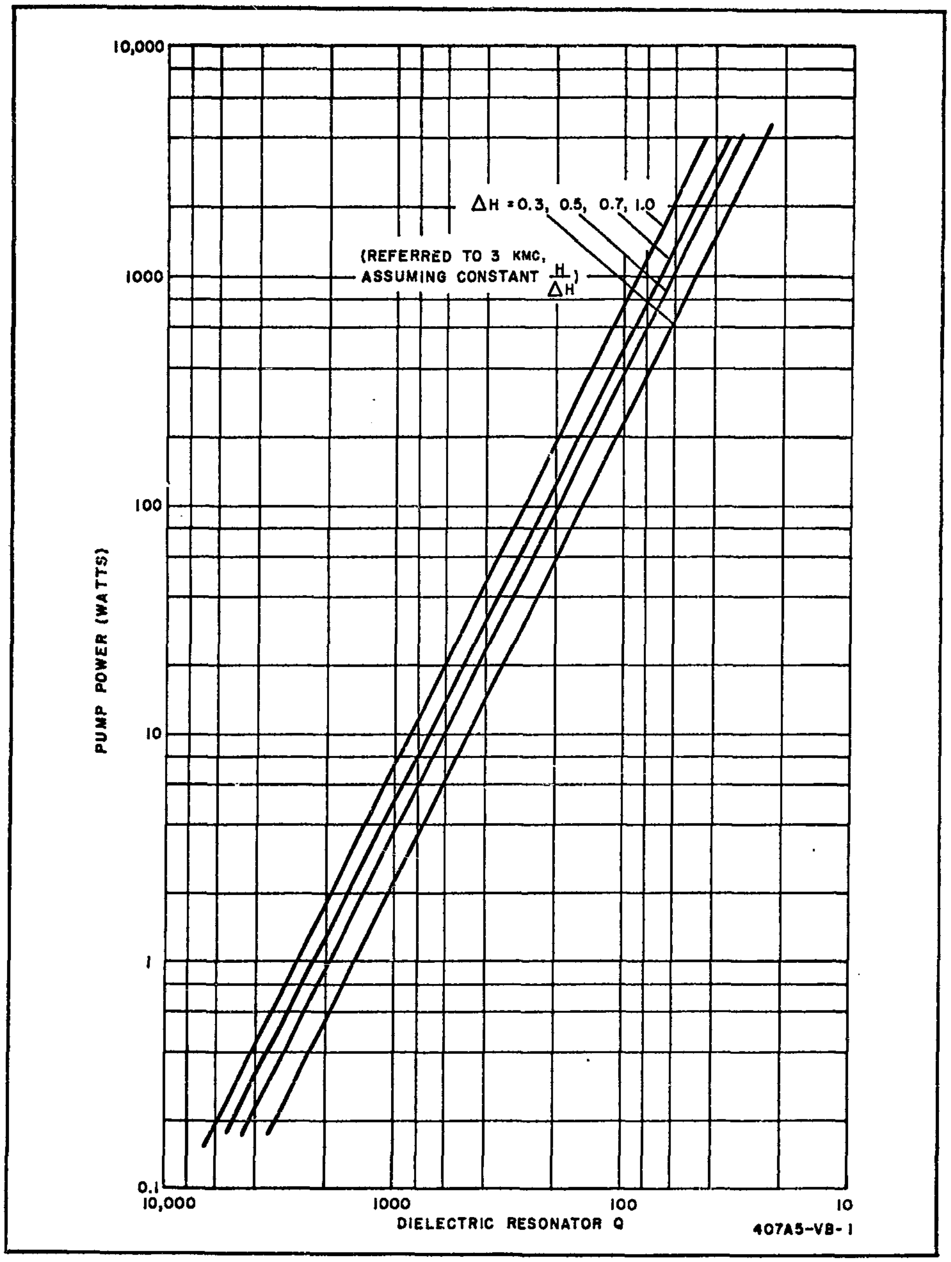

Figure 1. Pump Power Requirements

4.3 EXPERIMENT

The experimental work during the last quarter has increased our knowledge of the properties of potential dielectric rod materials. At present these are polystyrene, Stycast, and Ray-K, the last two being polystyrene-base ceramics. Properties measurements have been conducted at K_u-band and at M-band (4 millimeters) using reflection cavity techniques. A brief summary of some of the properties is given in table 1.

TABLE 1

PROPERTIES OF MATERIALS

Material	ϵ	tan δ		Machinability
		K_u	M	
Polystyrene	2.53	0.0013	0.006	Good, but tends to melt under machining
Stycast	13.5	0.002	0.004	Machines easily with carbide tools
Ray-K	12.2	0.002	----	Brittle

The relationship between the loaded Q and unloaded Q of a resonance has been derived more accurately for the reflection arrangement since the last quarterly report, allowing the calculation of loss tangents of the materials. The relation is

$$\frac{P_3}{P_1} = \frac{5\left(\frac{P_2}{P_1}\right)^2 + 2\left(\frac{P_2}{P_1}\right) + 1}{\left(\frac{P_2}{P_1}\right)^2 + 2\left(\frac{P_2}{P_1}\right) + 5} \tag{21}$$

where,

P_1 = Power reflected at nonresonance

P_2 = Power reflected at resonance

P_3 = Power reflected at the unloaded line width

Since machining problems make the use of Ray-K difficult in 4-millimeter resonant structures, Stycast appears to be the most suitable material and is being used for initial amplifier structures. Other potential materials are on hand to be tested later. These include lithium fluoride (Harshaw Chemical Company), alumina, and magnesium titanate (Trans Tech). All of these advertise low loss tangents and have dielectric constants from 9 to 15.

During the quarter the dispersive curves of Stycast have been worked out theoretically and experimentally to provide accuracy in the choice of dimensions for posts. This was done first by fabricating a number of posts in which the ratio of length to diameter varied. The first post had a diameter only slightly greater than the cutoff diameter of the dominant mode and was one-half wavelength long. This guaranteed that the resonance of lowest frequency was due to the HE_{11} mode, the dominant mode, thus establishing the dielectric constant with accuracy. Previous misidentification of modes suggested a value of $\epsilon = 15.3$ instead of the corrected value of $\epsilon = 13.5$. Rods of proper dimensions were used to work out incrementally the rest of the curves of the HE_{11} and H_{01} modes. The experimental results are plotted in figure 2.

The computer solution of the characteristic equation of the dielectric rod propagation structure for $\epsilon = 13.5$ is presented in the same figure. Curves for three other dielectric constants are given in figures 3, 4, and 5. These values were chosen because they correspond to the other materials on hand, polystyrene ($\epsilon = 2.53$), lithium fluoride ($\epsilon = 9.0$), and Ray-K ($\epsilon = 12.2$). The data for $\epsilon = 2.53$ overlaps and agrees with the results in the "Third Quarterly Progress Report on Investigations of Multi-Mode Propagation in Waveguides and Microwave Optics," published by Beam, et al., at Northwestern University.

Since the dielectric constants of R-1 and YIG are 13.5, one would expect that a sphere of either embedded in a Stycast rod would not affect the zero-field propagation characteristics of the rod. This has been borne out by experiments with two Stycast rods, one containing a wide line width unpolished R-1 ferrite sphere, the other containing a narrow line width YIG sphere.

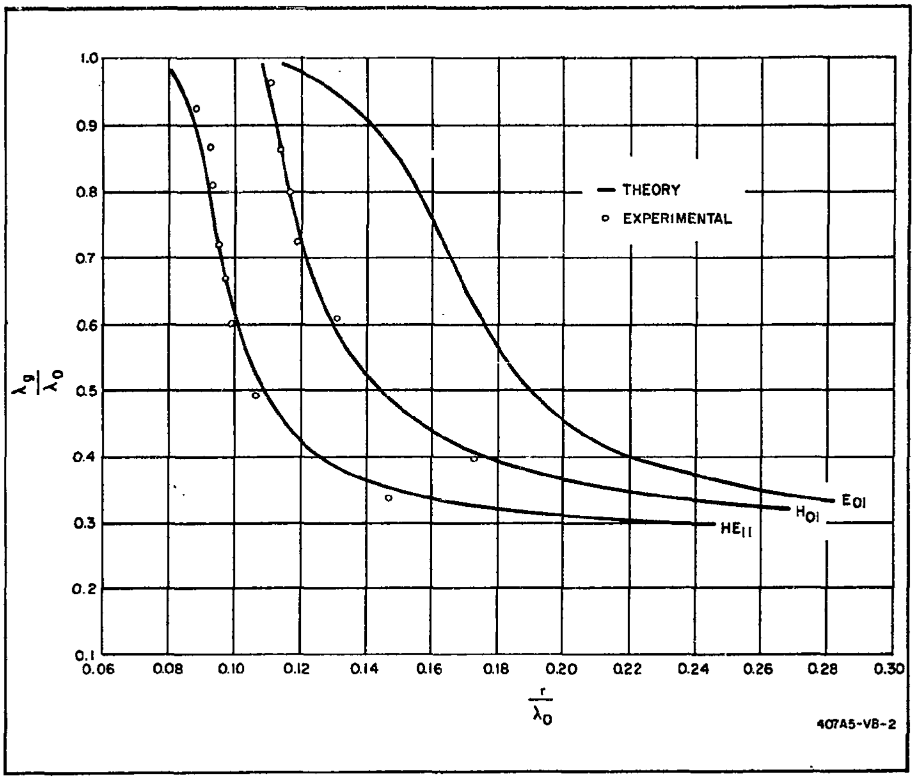

Figure 2. Dispersive Characteristics of Dielectric Rod Structure, ϵ = 13.5

Resonant frequencies agreed with theory about as well as those of the pure Stycast rods. The effect of a magnetic field will be discussed below.

The electromagnetic design of the amplifier was discussed in the last quarterly report. The design incorporates the modified semistatic parallel-pumped mode of operation. Initially a dielectric rod is being used which is capable of supporting simultaneous resonances in the HE_{112} and H_{013} modes and containing a narrow line width YIG sphere within which these two modes can interact with the uniform precession magnetostatic mode.

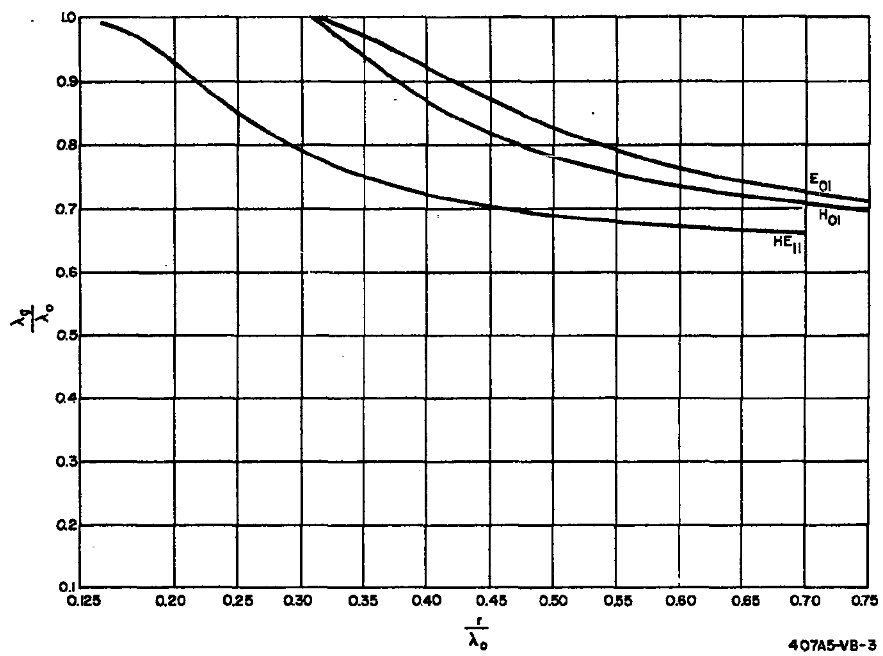

Figure 3. Dispersive Characteristics of Dielectric Rod Structure, $\epsilon = 2.53$

Similar problems must be solved in work with the dielectric rod and ferrite rod amplifiers. The main problems considered with the dielectric rod structure will be discussed in the following paragraphs: behavior and fabrication of posts, feeding the posts, and tuning the pump mode resonance. All of these are problems also of the ferrite rod.

First of all, the electromagnetic cavity modes and the magnetostatic mode will have mutual effects irrespective of parametric interaction. Coupling between the modes will result which may change the resonant frequency of the electromagnetic modes and furnish an increase in the effective propagation effects of the ferrite. To study the seriousness of

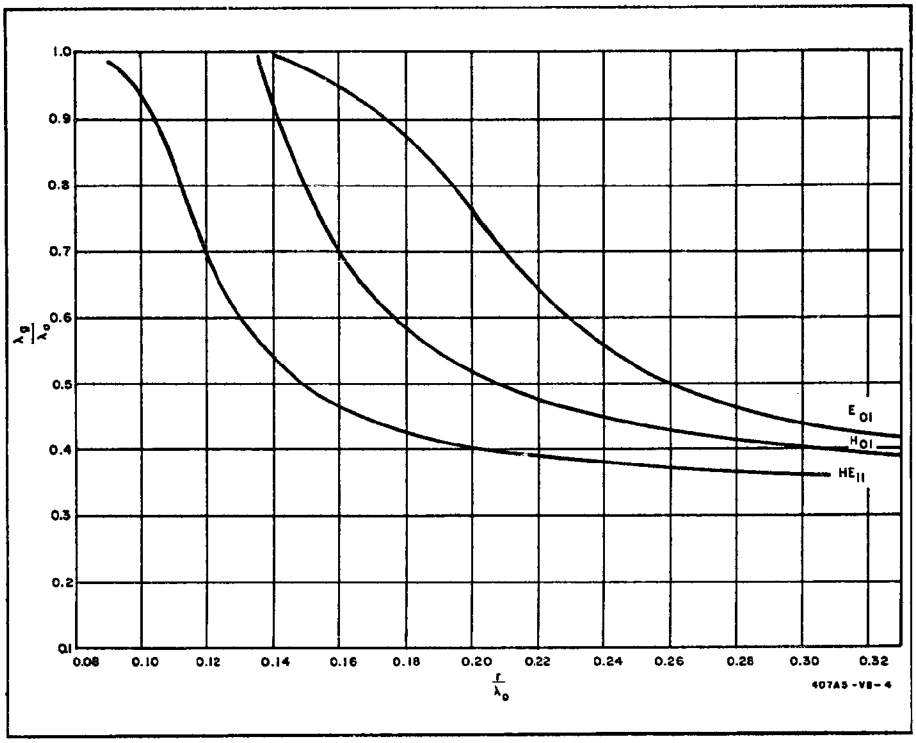

Figure 4. Dispersive Characteristics of Dielectric Rod Structure, $\epsilon = 9.0$

these effects, a Stycast rod structure with embedded YIG sphere was prepared for tests at K_u- and K-band. The behavior could then be scaled up to M-band.

The effect of the magnetic material on an electromagnetic mode is presented as a function of H in figure 6. The mode happens to be the HE_{111} which resonated at 13.75 kmc. The lack of effect of magnetic field except near the magnetostatic spectrum was observed for all electromagnetic modes Unperturbed cavity resonance should occur, therefore, when the magnetic field is far from the Walker mode spectrum, as will be the case in the present amplifier. The behavior in figure 6 would be expected of a ferrite

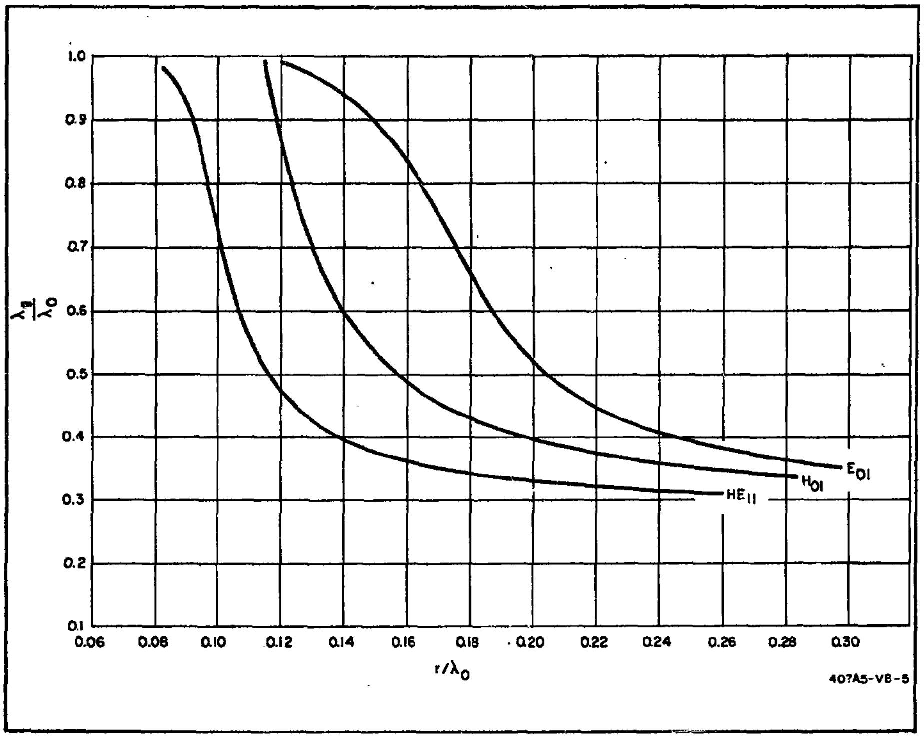

Figure 5. Dispersive Characteristics of Dielectric Rod Structure, $\epsilon = 12.2$

rod also. One would also expect this from the similarity of figure 6 to the experimental behavior of a ferrite sphere alone, in which case the cavity resonance is that of the sphere.*

The dielectric rod affects, vice versa, the magnetostatic spectrum of the sphere. This is manifested in increased propagation effects at a particular value of (kr_o), where k is the wave number of the incident wave and r_o the radius of the ferrite sphere. The same Stycast rod with YIG sphere was used. At a value of $(kr_o) = 0.19$, the effective gyromagnetic ratio had fallen

* Roberts, Auld, and Schell, Journal of Applied Physics, XXXIII, Supplement, (March 1962), 1267.

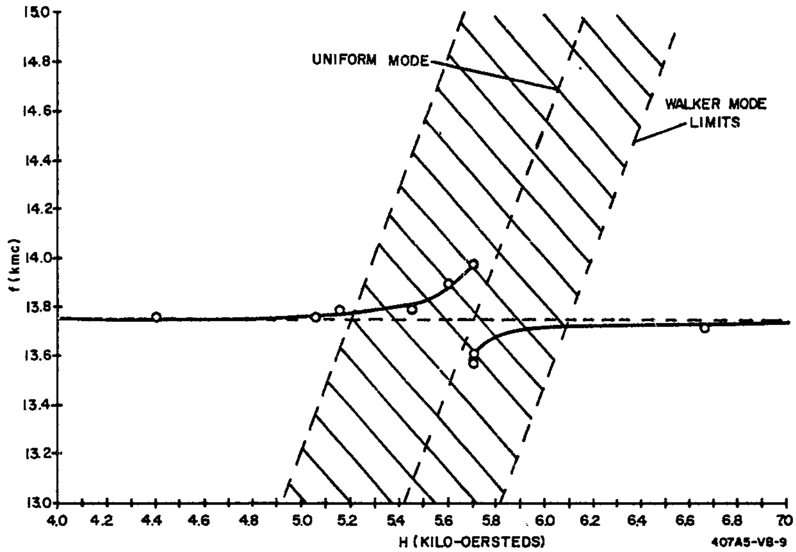

Figure 6. Magnetostatic Effect on Electromagnetic Resonance

to $\gamma_{eff} = \frac{\omega}{H_o} = 2.60$ for the uniform precession mode, which was identifiable amidst a sprinkling of fifteen observable Walker modes on the basis of the mode-charting work reported in Report No. 7. In that report, measurements of the same sphere in air gave a value of $\gamma_{eff} = 2.68$ at the same value of (kr_o). Since the final amplifier will be operating near $(kr_o) = 0.12$, the uniform mode will be easily available for use as the signal mode.

The Stycast rod structures are being machined on a lathe in half-length sections. Hemispheres are drilled in the ends to glue the YIG sphere into place. The dielectric constant of the glue (Q-dope) is low and can be raised by dissolving some high dielectric-constant powder, such as titanium dioxide, in it. Thus far, this has not been necessary. Finally, the structure is polished with optical powders to reduce the amount of scattering.

Another problem handled with the dielectric rod has been feeding the modes on the rod structure. Strong coupling (up to 30 db) has resulted by coupling into the end of the post through the side of the waveguide at a maximum of the standing wave. The behavior (including Q) of the side-wall and end-wall coupling are similar since each represents the same field configuration in the iris. However, the side-wall arrangement is necessary in order to fit the structure between the poles of a magnet.

Apparently, no systematic study of iris coupling to resonant rod structures has been made. A major effort would probably be required to understand well the effects of iris size and position. Some intuitive generalizations of iris-coupled metallic cavities and a few empirical rules have been applied with limited success. For example, the resonant frequency of a mode is liable to increase considerably as the iris is moved off-center with respect to the rod, and it is liable to decrease as the iris is enlarged. Apparently over-coupling is also possible. It has seemed most feasible to determine the most suitable coupling position for each rod individually and empirically.

A third problem is the need for "tuning" the resonant frequencies of the rod because of the fixed frequency of the pump source. A cylindrical metallic cavity at the end of the rod can be used to modify the resonant frequency, and such a cavity has been built to operate around 69 kmc. It can tune the rod through an iris in the plate at the end of the rod. In addition, a simpler and more effective method will be used first, adding a rectangular block of material of the same height, which can be moved toward the rod, between the plates. The resonant frequency is decreased by several percent without significant reduction of Q.

Consideration of these aspects of constructing, feeding and tuning has led to the design and fabrication of a structure, such as that shown in figure 7. The pump energy and dc magnetic field are fed parallel to the rod structure. This arrangement is similar to the post-between-parallel-plates described in Report No. 8, figure 1, except that K-band waveguide has replaced the plates, allowing the signal to be coupled into the YIG from the side. The other two walls of the waveguide are sufficiently far from the post that little or no modification of the resonant frequency should result. Several experiments have shown that waveguide will not easily couple directly to a non-magnetic rod structure when it is situated in the middle of that waveguide. This should reduce the amount of pump and idler energy leaking into the K-band guide. By placing the rod in the middle, only half of the amplified signal will be reflected. However, the other half will be absorbed in the load. This will be sufficient, nevertheless, for monitoring the parametric action on the signal. The tuner can be moved back and forth in a semicircle by a thin polystyrene rod protruding through the top of the K-band guide.

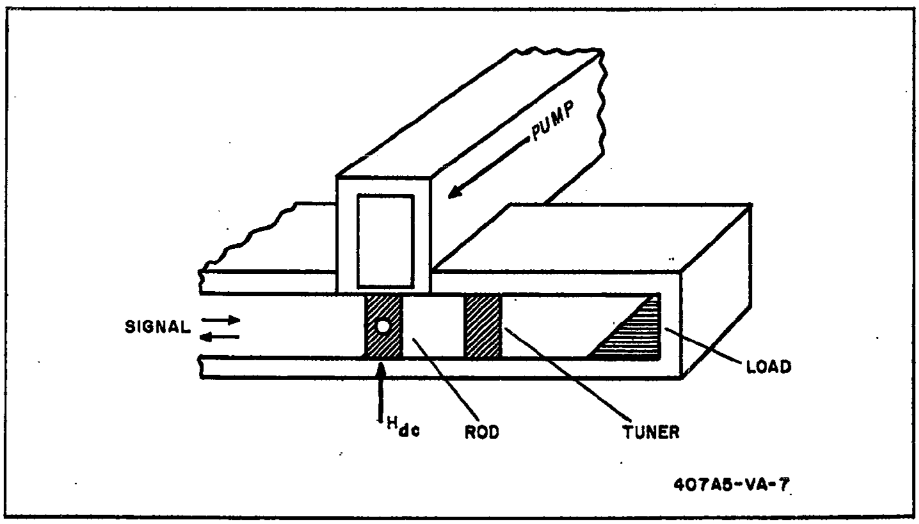

Figure 7. Amplifier Structure

A diagram of essential parts within the whole system is given in figure 8. The BL 221 magnetron has been used initially at 3.2 kw peak power and 0.7 watt average power. Attenuation of 7 db has been used immediately after the magnetron to reduce the VSWR to a safe value. A TRG calorimeter is

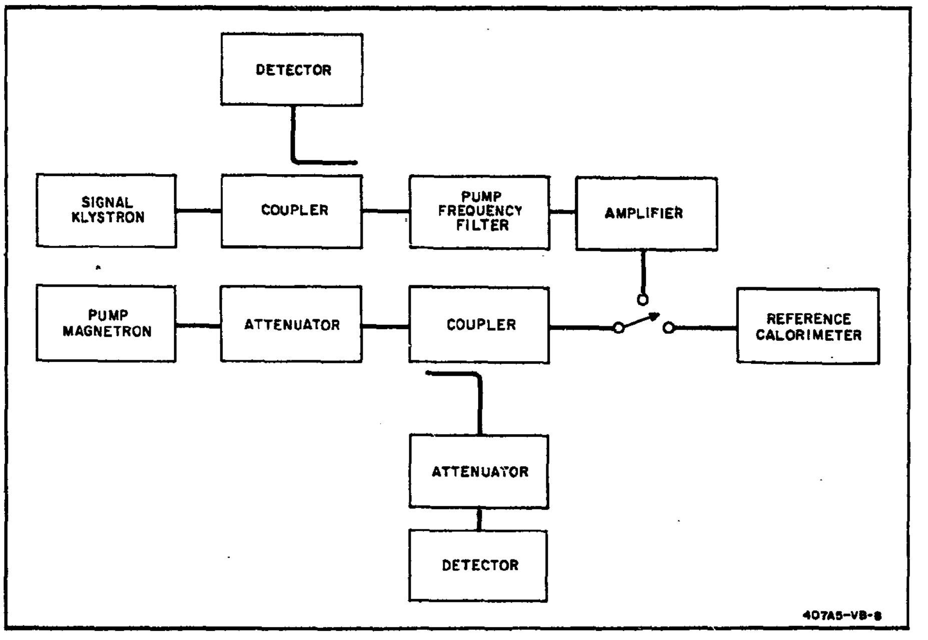

Figure 8. Pump-Signal Circuit

being used to measure power; a reference level can be initially set at the detector in the pump circuit and further measurements referred to this level. The high power portions of the circuits have been pressurized with sulphur hexafluoride to provide a high breakdown voltage. Filters are necessary to isolate the signal circuit from the large pump frequency power. A combination of E-H tuners and transmission cavity has been found to be an excellent filter and should be adequate.

During the past quarter these associated components have been tested out and the amplifier metallic structure has been fabricated. A polished 0.028-inch YIG sphere is available. Final measurements of dielectric constant at 4-millimeters are being made to determine the proper size of the Stycast post, but it will be approximately 0.170-inch by 0.043-inch, the length being chosen equal to the narrow dimension of K-band guide.

After these measurements are completed and the rod structure fabricated it will be situated in the metallic structure at the most suitable position with respect to the iris. The klystron can then be used for magnetodynamic spectroscopy. This will indicate the amount of tuning necessary and pinpoint the frequencies required for parametric behavior. The parametric modes can be tested individually by feeding energy into one mode at a time. After establishing a reference level with the calorimeter, the magnetron can be fed into the rod structure to test parametric oscillation. Finally, the structure can be tried out as an amplifier.

In Report No. 7, it was shown that a ferrimagnetic rod could be designed to support three appropriately chosen simultaneous magnetodynamic resonances. In line with this, five YIG single crystals have been obtained from Airtron which are large enough for the total resonant structure to be cut from them. Following the initial operation of the dielectric rod amplifier, spectroscopic measurements for a fully ferrimagnetic magnetodynamic amplifier will be begun.

5. CONCLUSIONS

The analysis conducted to help establish working relations in the design of the amplifier, though limited to the structure presently under experimentation, shows that magnetodynamic structures providing effective filling factor offer potential for operation at reasonable pump power. Lower loss dielectric materials must be found to support the electromagnetic resonance. Several materials which are presently on hand will be tested for low loss characteristics as soon as the present configuration is established.

Theoretical characteristic curves have been presented for dielectric rods with dielectric constants equal to 2.53, 9.0, 12.2 and 13.5. Experimental data using Stycast has confirmed the $\epsilon = 13.5$ curves. Scaled up models of dielectric rod-ferrimagnetic sphere structures have been built and tested for electromagnetic behavior, feeding of the modes, and tuning of resonances. A metallic structure of M- and K-band, cross-guided at an iris, has been built which will allow pump power from the BL 221 magnetron to be fed through the iris at a maximum of the standing wave into the end of the rod structure. The signal energy can couple into the magnetostatic mode from the side of the rod. The pressurization and pump-isolation systems have been tested in the pump-signal circuits. Construction of the final Stycast structure will permit testing the amplifier.

6. PROGRAM FOR NEXT INTERVAL

The work of the present period has been concentrated on experimentation on and construction of resonant structures, metallic housing and associated circuitry for a magnetodynamic amplifier configuration. Although it was hoped that an initial operating test could have been carried out by this time, it is expected that this will be accomplished shortly.

The analysis of this structure shows that amplification should be achievable for reasonably low pump powers provided a sufficiently low-loss dielectric material is found. Work will be directed toward a more general analysis to provide a measure of comparison and a means for optimizing the structure and mode of operation.

Several previously mentioned materials now on hand will be formed into resonant structures and tested at four millimeters as soon as operating tests are underway on the present Stycast structure.

Single crystal YIG cylinders, sufficiently large (0.150 inch long and 0.100 inch in diameter) to support four-millimeter electromagnetic resonance, have been obtained. Tests on these structures will begin in the next period.

7. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

7.1 PERSONNEL

Name	Title	Man-Hours
Robert A. Moore	Project Engineer	196
John D. Cowlishaw	Associate Engineer	440
James A. Miller	Associate Engineer	15

7.2 BIOGRAPHIES OF PERSONNEL

ROBERT A. MOORE - Dr. Moore received the degree of B.S. in electrical engineering from the University of Alabama in 1954. From then until 1958 he attended graduate school at Northwestern University. He received the degree of M.S. in 1956, and the degree of Ph.D. in 1960, both in electrical engineering. Since leaving Northwestern University, except for a short tour with the Army, he has been with the Westinghouse Electric Corporation where he conducted studies on atmospheric and ionospheric effects on electromagnetic propagation. For the past two years he has worked with the Applied Physics Group where he has conducted research work on microwave application of ferrimagnetic and ferroelectric materials. For a portion of his tour with the Army he was assigned to U.S. Army Signal Research and Development Laboratories where he studied the use of ferrimagnetic materials for microwave filters. Dr. Moore is a member of American Physical Society, Institute of Electrical and Electronics Engineers, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, Phi Eta Sigma, Sigma Pi Sigma.

JOHN D. COWLISHAW - Mr. Cowlishaw entered Calvin College in 1956. He received his B.S. and M.S. degrees in physics from the University of Michigan in 1960 and 1961. In July 1961, he joined the Westinghouse Student Training Program, working on military reconnaissance systems, ferrimagnetism, heat transfer in steam, and development of new thermoelectric

JOHN D. COWLISHAW (Continued)

materials. In November he assumed a permanent position with the Applied Physics Group working with ferrimagnetic materials for application to power limiters and parametric amplifiers. Mr. Cowlishaw is a member of the Institute of Electrical and Electronics Engineers.

JAMES A. MILLER - Mr. Miller entered the Pennsylvania State University in 1956 and received a B. S. in Engineering Science in 1960. In July 1960 he joined Westinghouse on the Graduate Student Program. In February 1961, he accepted a permanent position with the Digital and Analog Computation group of Air Arm where he is currently working on the application of large-scale computers to complex engineering problems. Mr. Miller is a member of Pi Mu Epsilon.

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material appealing for the design of resonant structures capable of supporting simultaneous electromagnetic and magnetostatic resonances. Results of loss tangent measurements of Stycast and other materials are given for 70 kmc and scale frequencies. Ways of coupling energy into the dielectric and magnetostatic modes were studied; experiments are discussed which resulted in the decision to couple to the pump mode from an iris in the side of the waveguide into the end of the rod and to couple to the YIG sphere directly from the side. A 10-kw, 70-kmc magnetron is being used to provide pumping power and has been tested at the 3.2-kw level in pressurized waveguide. The signal circuit, in addition to isolation through amplifier configuration, contains cascaded E-H tuners which provide a dynamic range of more than 15 db. Two mechanisms for tuning the resonance of the rod are available.

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IV. In ASTIA collection.
V. Secondary Report No. 407A5

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